

TEST RESULTS OF THE MODIFIED SPACE SHUTTLE MAIN ENGINE
AT THE MARSHALL SPACE FLIGHT CENTER TECHNOLOGY TEST BED FACILITYJ. Cook, D. Dumbacher, M. Ise, and C. Singer
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ABSTRACT

A modified space shuttle main engine (SSME), which primarily includes an enlarged throat main combustion chamber with the acoustic cavities removed and a main injector with the stability control baffles removed, was tested at the Marshall Space Flight Center's (MSFC) technology test bed facility. This one-of-a-kind engine's design changes are being evaluated for potential incorporation in the shuttle flight program in the mid-1990's. Engine testing was initiated on September 15, 1988, and has accumulated 1,915 seconds and 19 starts.

Testing is being conducted to characterize the engine system performance, combustion stability with the baffle-less injector, and both low pressure oxidizer turbopump (LPOTP) and high pressure oxidizer turbopump (HPOTP) for suction performance. These test results are summarized and compared with the SSME flight configuration data base.

Testing of this new generation SSME is the first product from the technology test bed (TTB). Figure test plans for the TTB include the highly instrumented flight configuration SSME and advanced liquid propulsion technology items.

INTRODUCTION

In July 1971, the National Aeronautics and Space Administration (NASA) awarded a contract to develop a reusable engine in an effort to depart from the Apollo program ideal of expendable engines and vehicles. It was from this initial contract that the SSME has evolved.

The SSME is a liquid oxygen/liquid hydrogen engine utilizing a two-stage combustion cycle. Figure 1 illustrates the SSME propellant flow paths. In the first stage, an extremely fuel rich mixture is partially burned in two preburners. The two exhaust streams of this combustion are then channeled to drive two high pressure turbopumps. The hot gas is finally injected into the main combustion chamber where final combustion of the propellants occur. The SSME is a throttleable engine which can operate from 65% rated power level (RPL) to levels exceeding 109% RPL. The normal 100% power level corresponds to 470,000 lb of thrust (vacuum) or 375,000 lb of thrust (sea level), with a specific impulse (Isp) of 453.5 seconds (vacuum). The SSME operates at a chamber pressure of 3,006 psia at 100% RPL with a mixture ratio of 6.0:1. The nozzle provides an expansion ratio of 77.5:1. Other engine particulars are given in Table I.

The modified SSME tested at MSFC's TTB is a one-of-a-kind engine. Its uniqueness comes from the elimination of the acoustic cavities and stability control injector baffle elements in the main combustion chamber (MCC) and from an increase in the MCC throat area of approximately 10%.

Testing at TTB was conducted to characterize engine system performance effects, combustion stability, and suction performance of the standard low pressure and high pressure oxidizer pumps, as well as the modified high pressure liquid oxygen (lox) pump. This test program also served as a pathfinder series to activate the TTB facility which will be used to test the highly instrumented flight configuration SSME. The test facility, test programs, and their objectives, results, and conclusions will be discussed in the following sections.

FACILITY

The TTB facility has a prestigious history in propulsion systems testing. The facility was constructed by MSFC in the early 1960's to static test fire the S-1C stage of the Saturn V. This stage consisted of five F-1 engines and developed 7.5 million pounds of thrust.

The static test stand is a vertical stand 406-ft high, including the main derrick boom. The superstructure is 267-ft high and the foundation is keyed into bedrock approximately 45 ft below grade. The structure has a gross area of 32,336 ft². Originally the structure was capable of supporting 7.5 million pounds of thrust, and could accommodate test articles 170-ft long and 40 ft in diameter. In the late 1970's, the test stand was modified structurally to conduct a series of tests on the space shuttle external tank (ET). Upon conclusion of this test series, the stand remained inactive until the modifications to accommodate the advanced SSME testing began in 1986. The current configuration is shown in Fig. 2. The stand was activated in 1988 with a series of

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cold flow checkout tests and a functional check of the Firex and deluge system. The technical specifications of the facility are given in Table II.

All control and instrumentation operations are controlled from a 27,000-ft² blockhouse located approximately 200 yards east of the test stand (Fig. 2). This building contains instrumentation signal conditioning and recording systems, closed-circuit television monitoring equipment, area warning systems, and the controls for all facility remotely operated valves. A tunnel system connects the blockhouse to the test stand. A General Electric programmable computer controls the sequencing and actuation of all facility valves. This unit also receives and analyzes approximately 125 channels of data that make up the facility automated cutoff system. The system is used to issue programmed and nonprogrammed test terminations. All facility valve actuation and other events are recorded on the discrete event evaluator (DEE). A typical printout from the DEE is shown in Fig. 3. This device allows for real time evaluation of facility valve operation.

The instrumentation system is capable of accepting 750 channels of digital data and 216 channels of analog data. Digital data can be recorded at a rate of 50 samples per second.

The liquid hydrogen storage facility consists of two vacuum-jacketed spherical tanks with a capacity of 480,000 gallons and can pump liquid hydrogen into the test stand run tank at a rate of 2,000 gallons per minute. The liquid hydrogen run tank capacity is 75,000 gallons. The lox facility can store 71,000 gallons in three horizontally mounted tanks. The lox storage facility can pump lox into the run tank at an approximate rate of 500 gallons per minute. The cylindrical lox run tank capacity is approximately 23,000 gallons.

The water for the Firex and deluge system and flame deflector are supplied from storage tanks capable of holding 7 million gallons. The test stand supply is fed by 13 diesel-powered pumps which are capable of delivering approximately 200,000 gallons per minute at a pressure of 150 psig to the test stand through a 96-in diameter pipe. This is equivalent to filling an average size pool every 7 seconds.

PATHFINDER SERIES

The overall goals of the initial TTB test series were twofold. The initial four tests, known as the Pathfinder series, were to demonstrate the enhanced capabilities of the modified Saturn test stand. The second series, consisting of 15 tests, was to evaluate and characterize the performance of an advanced SSME. A test series matrix is listed in Table III.

The Pathfinder series consisted of TTB-001 through TTB-004. This series was used to demonstrate the facility's capability to satisfy the engine interface requirements of propellant, pneumatic, hydraulic, and electrical supply; data acquisition; and chill down time as specified in the interface control documents. This was accomplished initially with a 1.5-second ignition test. After successfully meeting these requirements, the next test was a 15-second mainstage test at 100% RPL. This test demonstrated propellant supply system mainstage performance, flame deflector cooling capability, and served to check the effects of vibration on facility-mounted video and photographic equipment. The third test was prematurely terminated at 5.06 seconds due to an erroneous signal from accelerometers located on the main combustion chamber. Subsequently, a fourth test to check out the results of remotely mounting the main engine controller (MEC), and to demonstrate the facility's ability to vent and repressurize the lox run tank during a test was successfully completed with a duration of 45 seconds. The lox run tank venting profile was required to effectively evaluate the performance of the low pressure and high pressure lox pumps.

With the facility objectives successfully accomplished, the engine performance evaluation was then initiated.

TEST OBJECTIVES AND RESULTS

Fifteen tests conducted at the TTB facility accumulated the data required to characterize the performance of the modified SSME. The major objective of combustion stability was demonstrated during the initial eight tests. The second major objective was to evaluate the performance of the standard low and high pressure lox pumps, and to test a redesigned high pressure lox pump. The pumps were analyzed for suction performance with a variety of pump inlet conditions. A third major objective, specific impulse of the modified SSME, was determined using facility mounted thrust measurement and propellant flow instrumentation. These objectives and future test plans will be discussed in detail in the following paragraphs.

Combustion Stability

Combustion stability is a major design parameter of any propulsion system. High frequency combustion instability occurs when the combustion process is pressure and/or velocity sensitive at

time scales which allow coupling with the chamber acoustics. In the SSME, this usually occurs at low hydrogen temperatures and/or high oxidizer temperatures. The initial design of the SSME incorporated baffles which divided the coaxial injector faceplate into six compartments (Fig. 4A). The baffles are 2-in long and were designed to segment the more destructive fundamental acoustic modes. The forward area of the combustion chamber liner has a ring of acoustic cavities (Fig. 4B). These cavities are designed to dampen baffle compartment modes and other higher frequency modes. These stability aids were eliminated from the modified SSME design. An engine is regarded as dynamically stable if normal combustion is restored after being disrupted by an artificial device. The usual method to determine stability is to temporarily disrupt the combustion process with a nondirectional pyrotechnic device. Stability is determined by the time required for the engine to return to normal combustion conditions.

To demonstrate the combustion stability characteristics of the modified SSME, small explosive charges were attached to the main injector face and positioned near the thrust chamber wall where a pressure antinodal point is present for all resonant modes of instability (Fig. 5 and 6). Charges ranged from 10 grains to 15 grains in size and were detonated during the engine start transient. Figure 7 gives a cross section of a typical stability rating bomb. Each test included the detonation of two charges. Figure 8 lists the time of detonation, size of charge, and chamber pressure at time of detonation for each test. Triaxial accelerometers were the principle measurements used to detect combustion chamber resonances. The triaxial accelerometers were physically mounted external to the main combustion chamber (Fig. 9). Axial accelerometers were installed at the engine gimbal mounts. A fluctuating pressure measurement was placed in the main injector lox inlet dome.

The TTB combustion stability test series consisted of eight tests, and resulted in 16 successful bomb detonations. Fifteen of these detonations occurred at the targeted combustion pressure with only one bomb having to be prematurely detonated when a test was cut by an erroneous signal. The induced flow instabilities had minimal effect on engine start or thrust buildup. As predicted, the pressure oscillations were dampened out within an average of 6 msec revealing no instability (Fig. 10).

LPOTP and HPOTP Performance

The enlarged throat MCC had several beneficial qualities. Lowering of system operating pressures and temperatures created a lower stress level resulting in increased hardware life. The TTB test program was used to evaluate the low and high pressure lox pumps' ability to operate at these lower system pressures and higher flow coefficients (Fig. 11). Figure 12 gives the thrust profile of a typical test in which the low pressure lox pump inlet pressure was decreased to evaluate the pump suction performance.

As predicted, initial tests revealed some degradation in the suction performance of both the low pressure and high pressure production configuration oxidizer pumps when the engine is operated at low net positive suction pressures (NPSP) during the vented portion of the test. The HPOTP cavitation (head fall off) increased to 11% at 104% RPL (20 NPSP) and 13% at 109% RPL (40 NPSP). The LPOTP also showed significant suction performance loss at the 104% RPL (20 NPSP) (Fig. 13). A second test series was conducted to evaluate the modified inlet HPOTP performance. The test revealed less than 5% head fall off in the LPOTP at 104% RPL with 22.5 psi NPSP and only a minimal 3% cavitation in the HPOTP. Significant increase in suction performance was achieved utilizing the 15 vane inlet and thin blade inducer versus the production configuration HPOTP. Figure 14 gives a comparison of the different pumps. The next test in the series revealed some cavitation, approximately 3% in the LPOTP at 109% RPL with 26 psi NPSP, and increased cavitation, approximately 6.5% in the advanced HPOTP. These results show a significant performance improvement in the advanced HPOTP with the large throat engine. The low pressure oxidizer turbopumps will require slight redesign of the impeller to achieve acceptable system performance characteristics.

Specific Impulse Testing

The MCC of the advanced SSME incorporated an enlarged throat diameter which increased the throat area by 10%. The MCC also featured optimized coolant channel geometry and a recontoured converging-diverging section designed to reduce heat loads. Figure 15 gives a comparison of the existing SSME MCC to the enlarged throat design.

One major concern of the advanced design was the predicted loss of specific impulse. The increased throat diameter allows the operation of the engine at lower chamber pressure while maintaining the same thrust. However, lower chamber pressure and reduced area ratio results in a theoretical reduction in Isp of 2 seconds. Reduced MCC film coolant and removal of the injector baffles and acoustic cavities increases the combustion efficiency. A residual performance concern exists, however, with the potential for a strong shock in the divergent section of the MCC (due to turnback angle). A major objective of the test series was to quantitatively measure the combined effect of these changes to the baseline SSME.

Thrust from the advanced engine was measured at TTB using a series of three vertical load cells arranged in 120-degree intervals attached to the facility at the engine platen. The load cells are accurate to within 0.25% of their 0 to 250 klbf range. The load cells were calibrated at ambient and cryogenic temperatures prior to each test. The propellant flowrates were recorded using flowmeters installed in the facility suction lines. A special camera system was installed in the flame deflector to investigate the predicted shock. The specific impulse of the engine was approximately 452.56 seconds which is within the statistical data base of the flight engines. No evidence of a strong shock was indicated by either the photographic analysis or the measured thrust. The levels of specific impulse recorded during the test series are given in Table IV. These results will be compared to the data acquired during tests scheduled to be conducted at the facility used for flight engine acceptance tests.

ADVANCED TECHNOLOGY TESTS AND RESULTS

The tests conducted at TTB were also used to advance the technology of the flight configuration SSME. One of the technology issues investigated on the modified engine was to establish a smoother start/stop transient curve by the modification of the sequence timing on two of the engine oxidizer valves. Another TTB test provided data on the main fuel valve (MFV) continuous helium purge. This purge is required to eliminate the possibility of nitrogen build-up on the valve ball. The test demonstrated that the continuous fuel system helium purge would eliminate formation of ice on the MFV ball. This ice could cause leakage resulting in a fire during an on-pad abort. A third issue investigated during testing of the modified engine was the engine's capability to throttle below 90% RPL with a flight nozzle at sea level. Power levels of 86% to 90% were successfully demonstrated during TTB-019 (Fig. 16). The ability to throttle to levels less than 90% provides greater flexibility in the shuttle ascent trajectory.

The test program conducted at TTB proved to be extremely successful. It demonstrated the capability of the test facility and provided a detailed characterization of the modified engine. Future plans of the technology test bed are to test a highly instrumented flight configuration SSME. The highly instrumented engine includes over 500 measurements. These measurements include the installation of Venturis to provide propellant flow characterization. The design also includes numerous internal thermocouples and strain gauges in the turbomachinery to provide data necessary to enhance the understanding of current pump configurations and to aid in the design of future systems. Test plans also include testing the newly developed alternate turbopumps, and characterization of the Block II SSME configuration planned for use on the space shuttle in the mid to late 1990's.

ACKNOWLEDGMENTS

The authors would like to thank all the civil service and contractor personnel who worked to make the TTB program a success. This includes the schedulers, planners, inspection personnel, and test conductors. The authors would like to especially thank the Consolidated Industries personnel who were involved in the day-to-day test operations. The high level of efficiency provided by this group was a key factor in accomplishment of the numerous goals of the program.

REFERENCES

1. H. Dennis, J. Hutt, and T. Nesman, "Stability Testing of a Modified Space Shuttle Main Engine."
2. D. Dinkins, "Advanced Engine Characterization Test Series Test Report."

Table. I. SSME Particulars.

<p>MAXIMUM THRUST: (109% POWER LEVEL)</p> <p>SEA LEVEL.....408,750 lbs VACUUM.....512,000 lbs</p> <p>PRESSURES:</p> <p>HYDROGEN PUMP DISCHARGE.....6872 psia OXYGEN PUMP DISCHARGE.....7936 psia COMBUSTION PRESSURE.....3277 psia</p> <p>FLOWRATES:</p> <p>TOTAL.....1130 lb/sec.....22557 gpm HYDROGEN.....160 lb/sec.....16436 gpm OXYGEN.....970 lb/sec.....6121 gpm</p>	<p>POWER:</p> <p>HIGH PRESSURE PUMPS HYDROGEN.....74928 horsepower OXYGEN.....28229 horsepower</p> <p>WEIGHT.....7000 lbs</p> <p>LENGTH.....14 feet</p> <p>DIAMETER.....7.5 feet</p> <p>PROPELLANTS:</p> <p>FUEL.....Liquid Hydrogen OXYGEN.....Liquid Oxygen</p>
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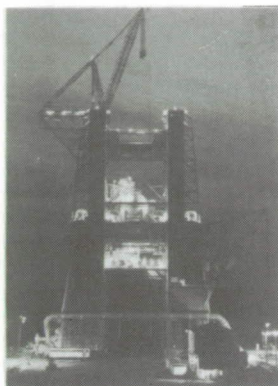
Table II. Facility Specifications.
**TECHNOLOGY TEST BED
KEY ELEMENT - ADVANCED ENGINE
TEST FACILITY**

TEST STAND

- 750,000 THRUST
- SINGLE POSITION ACTIVE
- SECOND POSITION AVAILABLE
- 23,500 GALLONS LOX
- 75,000 GALLONS LH₂

INSTRUMENTATION

- 750 CHANNELS DIGITAL
- 216 CHANNELS ANALOG
- 992 CHANNELS DISCRETE
- HIGH SPEED DATA DISTRIBUTION
- HIGH SPEED MOVIE CAMERAS
- CLOSED CIRCUIT T.V.



SUPPORT FACILITIES

- 450,000 GAL GROUND LH₂
- 7,000,000 GALLONS COOLING WATER
- TEST CONTROL CENTER
- FABRICATION BUILDING
- LOGISTICS AND RECEIVING BUILDING

PERSONNEL

- FULL TIME TEST CREW
- FULL TIME TECHNICIANS

DIAGNOSTICS

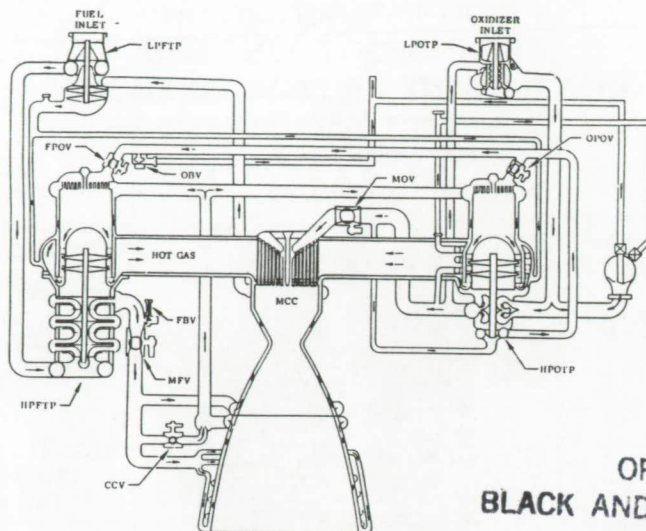
- STAND MOUNTED SYSTEMS
- TOWER LEG HOUSED SYSTEMS
- TEST CONTROL CENTER HOUSED SYSTEMS

Table III. Advanced Engine Characterization Test Series Primary Objective Matrix.

PRIMARY OBJECTIVE DESCRIPTION	TEST NUMBER														
	005	006	007	008	009	010	011	012	013	014	015	016	017	018	019
COMBUSTION STABILITY EVAL.	X	X	X	X		X	X	X	X						
ENLARGED THROAT MCC EVAL.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ADVANCED PUMP PERF. EVAL.			X	X	X	X	X	X	X					X	X
THRUST MEAS. ISP DETERMINATION								X	X	X	X	X	X	X	X
START AND S/D SEQUENCE CHANGE										X	X	X	X	X	X
88% RPL OPER. W/ FL. NOZZLE														X	
86% RPL OPER. W/ FL. NOZZLE															X

Table IV. Specific Impulse Testing Results.

TTB TEST NUMBER	DURATION (SECS)	Isp (SECS)
TTB-015	150	452.9
TTB-016	165	451.8
TTB-017	160	449.5



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Fig. 1. SSME Propellant Flow Schematic.

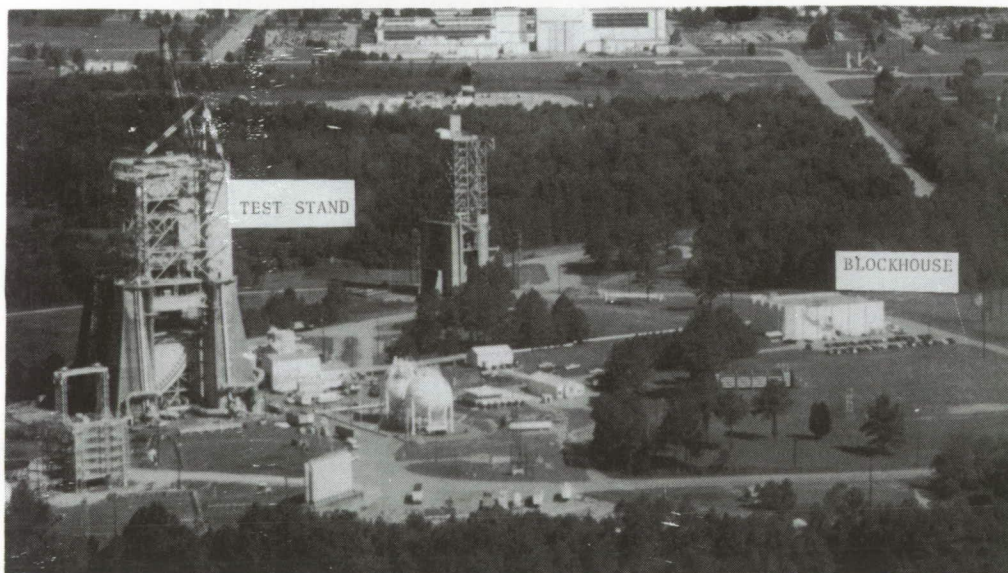


Fig. 2. Aerial Photograph of MSFC Technology Test Bed.

TECHNOLOGY TEST BED DATA BOOK						
CHRONOLOGY OF EVENTS						
TEST: TTB 019						
T(0) REFERENCE TIME 90:102:12:58:02.789						
TIME OF DAY	DELTA(TO)REF	STATE	TTBMSID	NOMENCLATURE	UNITS	
90:102:12:57:40.823	-21.9660	OFF	F45K7561W	EXIT IGNITER GLOW PLUG POWER ON	EVENT	
90:102:12:57:55.715	-7.0740	ON	F93K7574W	AUTO SEQUENCE START COMMAND	CHD	
90:102:12:57:55.723	-7.0660	ON	F93K6311W	AUTO SEQUENCE START	EVENT	
90:102:12:57:55.723	-7.0660	ON	F93K7668W	RUN TIME CLOCK	EVENT	
90:102:12:57:55.731	-7.0580	ON	F42K7476W	OPEN LOX POGO REDIRCULATION	CHD	
90:102:12:57:55.733	-7.0560	OFF	F46K7188W	ENG GH2 OVBRD BLEED HE PURGE ON	EVENT	
90:102:12:57:55.921	-6.8680	OFF	F93K7574W	AUTO SEQUENCE START COMMAND	CHD	
90:102:12:57:56.481	-6.3080	OFF	F42K7477W	LOX POGO REDIRCULATION CLOSED	EVENT	
90:102:12:57:57.341	-5.4480	ON	F42K7478W	LOX POGO REDIRCULATION OPEN	EVENT	
90:102:12:57:59.547	-3.2420	OFF	F42K7491W	ENABLE ENGINE LOX CHILLDOWN	CHD	
90:102:12:57:59.601	-3.1880	ON	F93K7632W	FACILITY ENGINE START TIMER	EVENT	
90:102:12:57:59.603	-3.1860	ON	F93K7674W	CAMERA SEQUENCE 2 ON	EVENT	
90:102:12:57:59.603	-3.1860	ON	F93K7673W	CAMERA SEQUENCE 1 ON	EVENT	
90:102:12:58: 2.313	-0.4760	OFF	F93K7668W	RUN TIME CLOCK	EVENT	
90:102:12:58: 2.789	0.0000	ON	F93K7668W	RUN TIME CLOCK	EVENT	
90:102:12:58: 2.789	0.0000	ON	F93K7633W	CADS ENGINE START COMMAND	EVENT	
90:102:12:58: 2.789	0.000	ON	F93K7720W	TIME PULSE OVERRIDE	EVENT	

Fig. 3. Typical Discrete Event Evaluator Plot

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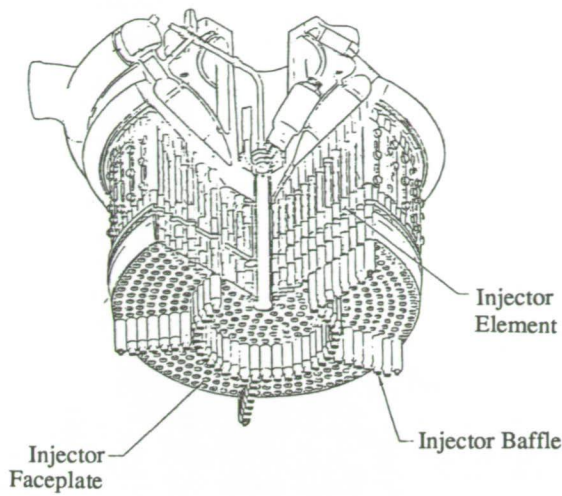


Fig. 4a. Main Injector.

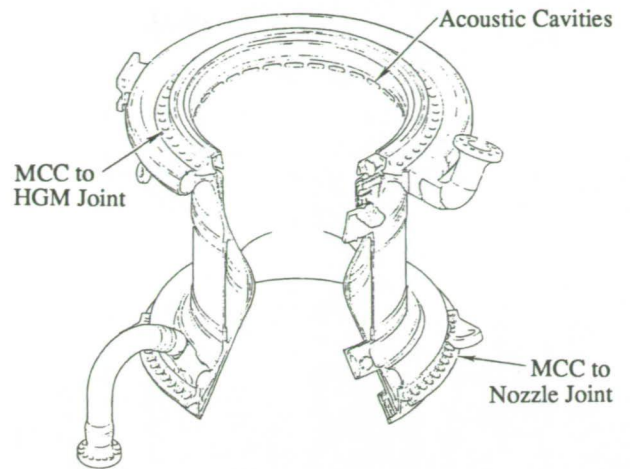


Fig. 4b. Main Combustion Chamber.

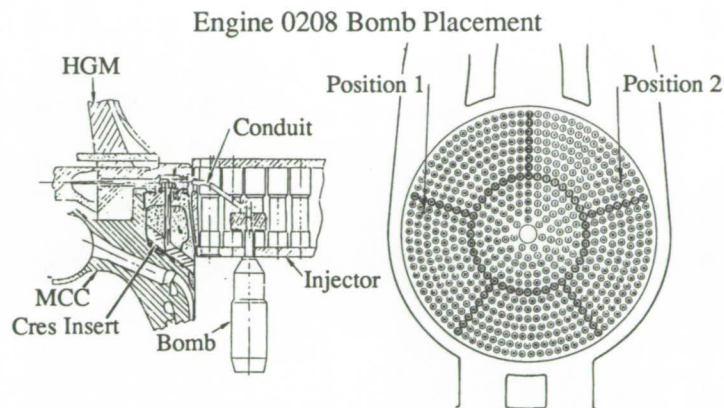


Fig. 5.

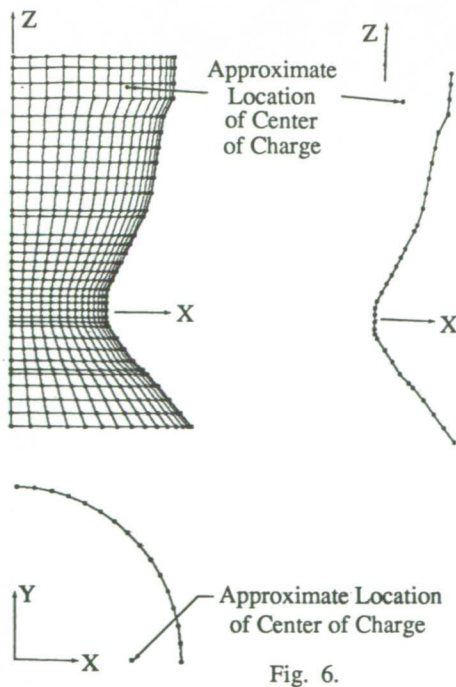


Fig. 6.

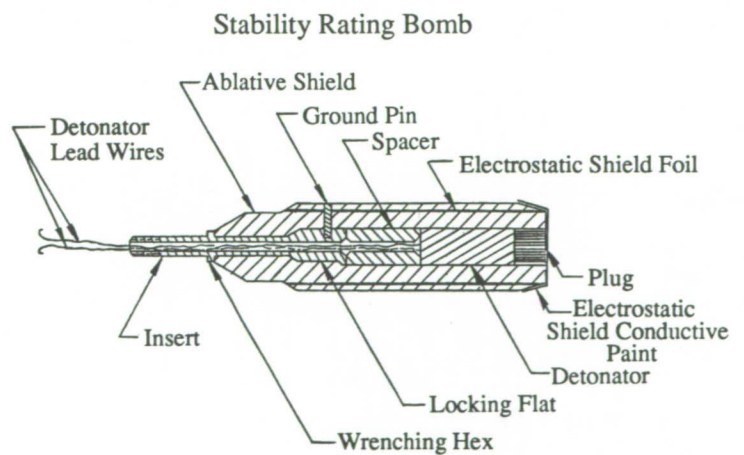
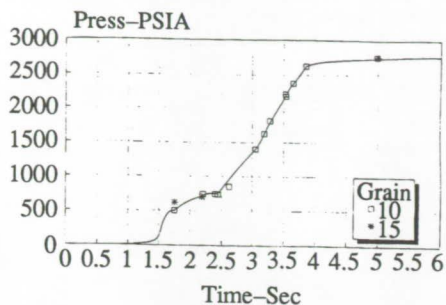


Fig. 7. Bomb Cross-Section.



t	TTB5	TTB6	TTB7	TTB8	TTB10	TTB11	TTB12	TTB13
1.75								
2.20								
2.40								
2.43				740	710	500	700	620
2.62						735		
3.05								
3.19		1,400	850					
3.28								
3.53								
3.64	2,220					1820		1,630
3.85								
4.98		2,620		2,360				2,185
5.00	2,755							
							2,760	

* 15 Grain

Fig. 8. Bomb Detonation Matrix.

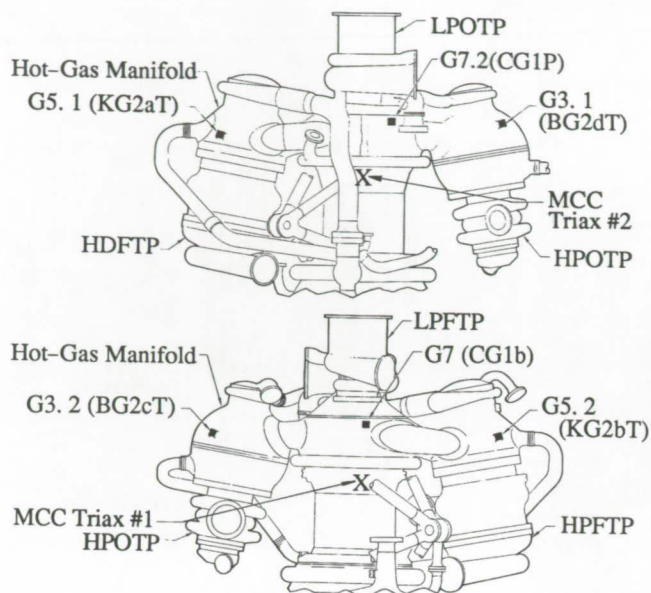


Fig. 9. Accelerometer Locations.

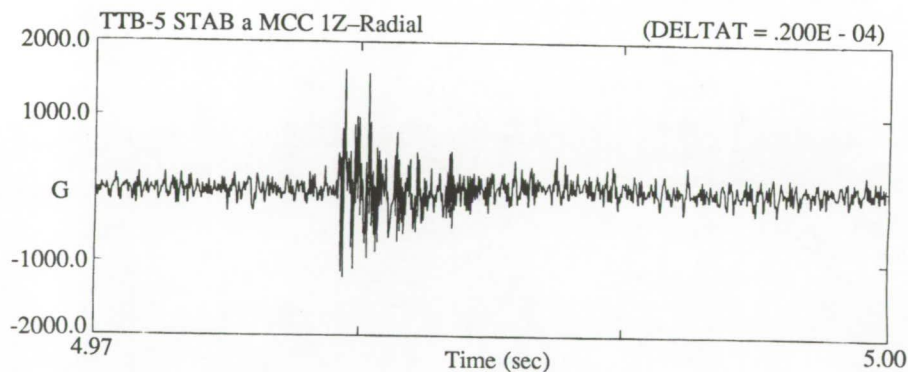


Fig. 10. Pressure Fluctuation Dampening.

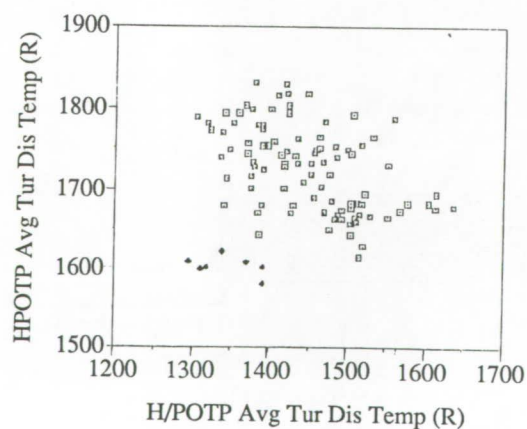


Fig. 11. Modified Engine Pump Comparison.

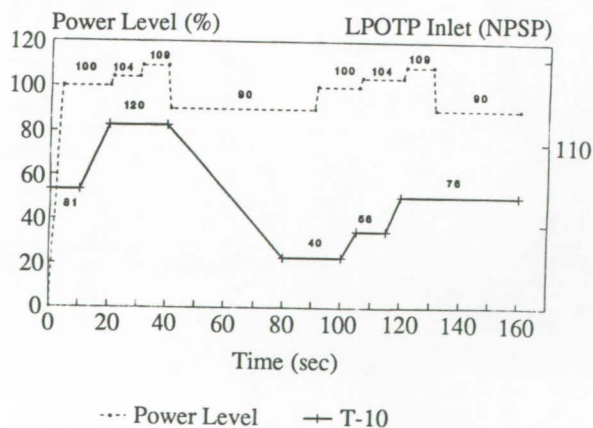


Fig. 12. Pump Performance Test Profile.

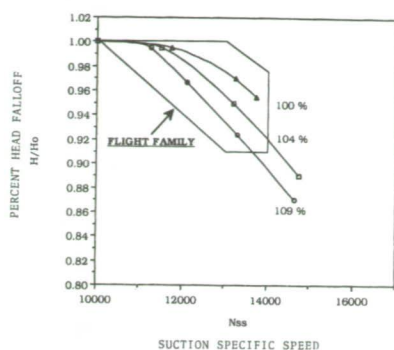


Fig. 13. Modified SSME Turbomachinery Performance.

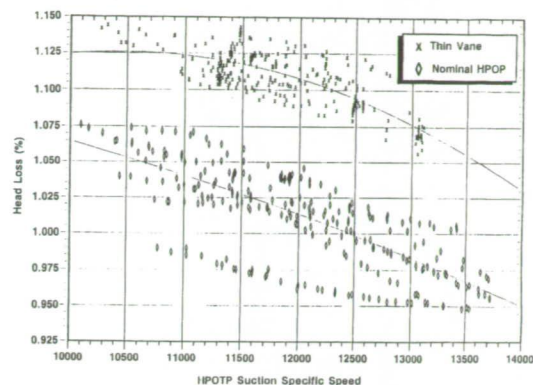


Fig. 14. 15 Vane Inducer vs Flight Configuration.

ENHANCED MAIN COMBUSTION CHAMBER COOLING

o SIGNIFICANT BLANCHING/ CRACKING

PHASE II
50%

MODIFIED SSME
NONE

PHASE II MCC (FLIGHT)

ENLARGED THROAT MCC

Channel Width (CW), in.	0.0400	0.035
Land Width (LW), in.	0.0435	0.045
Wall Thickness (WT), in.	0.028	0.025
Number of Coolant Channels	390	430
Hot Gas Wall Temperature, F	1000	900
MCC Coolant Disch. Temp. (@ 100 % PL), R	466	501

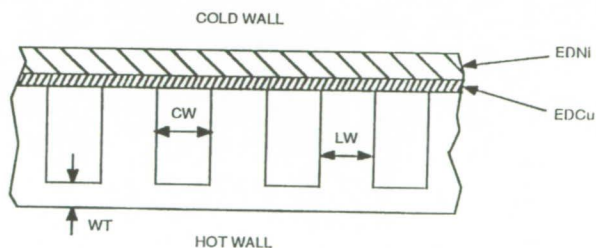


Fig. 15. Modified SSME vs Current SSME.

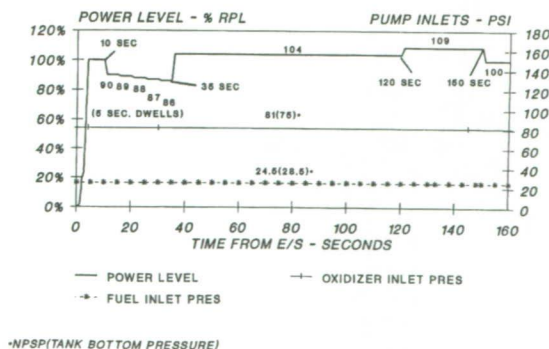


Fig. 16. Advanced Throttling Profile.